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# The Energy Intensity of the Internet: Edge and Core Networks

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**Abstract.** Environmental assessments of digital services seeking to take into account the Internet's energy footprint typically require models of the energy intensity of the Internet. Existing models have arrived at conflicting results. This has led to increased uncertainty and reduced comparability of assessment results. We present a bottom-up model for the energy intensity of the Internet that draws from the current state of knowledge in the field and is specifically directed towards assessments of digital services. We present the numeric results and explain the application of the model in practice. Complementing the previous chapter that presented a generic approach and results for access networks and customer premise equipment, we present a model to assess the energy intensity of the core networks, yielding the result of 0.052kWh/GB.

**Keywords:** Internet, Energy Efficiency, Energy Intensity, Video Streaming, Online News

## 1 Introduction

Assessments of individual digital services such as video, web browsing or file downloads delivered over the Internet need to factor in a share of the energy consumption by the network – called an energy footprint – as the use-phase part of the environmental impact from the service life cycle. Most commonly, such a footprint is derived from multiplying an estimate of average network energy intensity per bit with the data volume transferred by the digital service. The energy intensity for an individual network device such as a router is the ratio of its power consumption (measured in watts) and its throughput capacity (measured in bits per second). The energy intensity of the network is the sum of the energy intensity of all devices along a route through the network between two endpoints, usually a client and a server.

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Past studies, such as [1-4], have applied differing models and assumptions [5]. This has led to increased uncertainty and reduced transferability of assessment results. Meanwhile, existing standards for environmental assessment of IT services [6-7] do not recommend concrete models and parameterization. Thus, those wanting to perform environmental assessments of digital services are left without a guideline on how to assess network energy consumption.

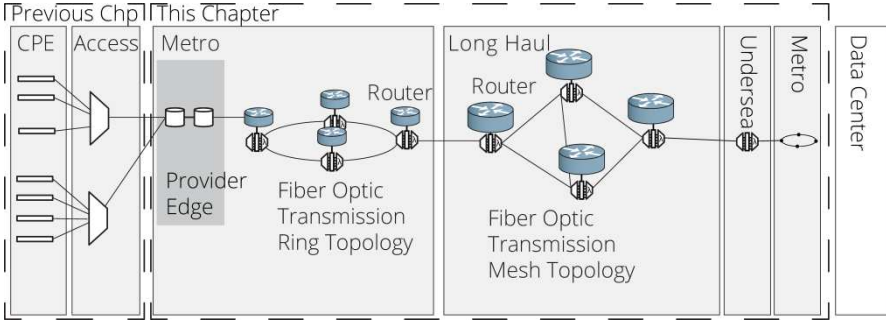
In this text, we present a bottom-up model for the energy intensity of the Internet that draws from the academic state of the art and is specifically directed towards assessments of digital services. We present the numeric results and explain the application of the model in practice.

We begin with a description of the structure of the Internet in the next section. Based on that we present the models and their parameterization in Section 3. Subsequently, in Section 4 we present the numerical results and finish with a discussion of their practical application.

## 2 Background

### 2.1 The Structure of the Internet

Development of the Internet data network began as a service delivered on top of the telephone network and gradually separated from the latter as generations of network technology replaced one another. Our description is focused on the current state of the art in Internet Service Provider (ISP) networks. As a result, some legacy technology that might still be in operation is not presented here and may contribute to the uncertainty of the models. Interested readers are referred to [8-10] for more detail.



**Fig. 1.** Structure of the Internet for residential customers. Customer Premise Equipment (CPE) in the home, such as a DSL or cable modem, connects to the access network terminals that aggregate data traffic in a neighborhood and connects to provider edge switches. In the metro network traffic from several edge network devices is aggregated and passed to the long haul network for long-distance transmission to the metro network connecting to the data center where the service provider operates servers.

One frequently applied decomposition of the network, and the one adopted here, distinguishes the four layers of access, edge, metro and long haul networks as displayed in Figure 1. Metro and long haul networks are frequently referred to as network core. As data travels from access to core, each layer handles increasing volumes of traffic and provides aggregation of traffic from multiple links in previous layers. These networks are frequently operated by separate organizations, which are contract with one another and transport data traffic on one another's behalf.

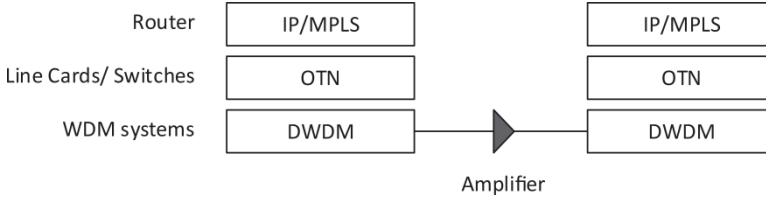
Consumers operate customer premise equipment (CPE) such as modems and routers to connect to their broadband service provider network through a feeder network, also often referred to as the last mile or local loop, such as the copper lines of the telephone service that provide DSL connectivity, coaxial cable for cable connection or fiber optic cables. In the case of DSL and cable, signals from the customer modem are disaggregated into a data and a voice/ video stream in a multiplexing node such as a DSLAM or a CMTS, which is connected to a metro network. The specific types of devices operated in the access network depend on the technology that is required to be supported in the access network.

Traffic by multiple access network multiplexers is typically aggregated by Ethernet switches before being passed on to the next higher network hierarchy. These switches provide subscriber traffic management to the broadband service provider. The specific type of device varies depending on the access network technology. In the case of DSL the DSLAMs connect via switches to broadband remote access servers (B-RAS). In the case of cable, the CMTS provides the subscriber management and modem function in one device.

Traffic then passes an Internet service provider (ISP) edge (PE) router and at this point enters the metro network. This part of the metro network is sometimes referred to as "edge network." The ISP is frequently a separate organization from the broadband service provider. The majority of ISP networks apply multiprotocol label switching (MPLS) for their greater traffic management capabilities over earlier systems and these provider edge routers are the ingress and egress nodes to the MPLS network. At the PE router the decision is made which part of the traffic to route outside of the metro network towards the long haul network, depending on the location of the data packet. The destination might be a server in a data center or another customer computer in the case of P2P traffic. Campus networks and data centers can connect directly to provider edge routers that manage their services.

While the routing (i.e., finding paths between networks) in metro and long haul networks is performed on the IP/MPLS layer, the physical connection between routers is established by fiber optic cables using either time division or wavelength division multiplexing (TDM or WDM). In the optic core, transport is realized by dense wavelength division multiplexing (DWDM) networks. As [10] note, use of DWDM in the metro networks is less frequent, and TDM links are used instead. Commonly, a wrapper for TDM channels called optical transport network (OTN) is used to simplify the existing infrastructure and provide TDM transport in metro networks. The conversion of IP packets to the containers that these various protocols use is implemented in IP router line cards.

Metro as well as long haul routers are composed of a chassis that provides slots for line cards, which are also called interface modules or port cards. The line card then hosts slot cards. Routers perform routing, in electronic circuitry, and via the OTN line cards connect to fiber optic cables for transport. The fiber cables then connect to WDM terminal systems.



**Fig. 2.** Illustration of the device stack in core networks. IP/MPLS (Internet Protocol, Multi Protocol Layer Switches) routers perform routing functions (i.e., establish a route between source and destination across networks) and DWDM (Dense Wavelength Division Multiplexed) systems add or remove wavelengths to fiber cable links. The IP/MPLS devices connect to the DWDM systems over OTN fiber connections. Depending on the distance between network nodes, the signals traveling along links are amplified.

Figure 2 is an illustration of the technology stack. At the top, a router determines the destination for a (labeled) packet, then sends it out via an OTN interface module to the WDM system where the light wavelength containing the data is added to a channel. At the next WDM terminal, the wavelength is either passed on to the next DWDM node or dropped from the wavelength and send to the router. The link between two terminals is called a hop. The number of routers in a route of  $n$  hops is thus  $n+1$ <sup>1</sup>. If the distance exceeds 80 to 100km, then amplifiers are placed on the fiber cable.

Intercontinental traffic usually traverses undersea cables that are terminated on either side with a particular type of WDM terminal and amplified.

The majority of end user traffic is directed to servers in data centers. These are directly connected to metro networks by edge routers.

A model of the energy footprint takes into account the energy consumption by all these device types. The majority of web traffic traverses the network between a single source and destination, also called “unicast”<sup>2</sup>. The number of devices in each layer is then equivalent to the diameter of the network segment. The particular segments that are being traversed may differ depending on the particular service. For example, a significant portion of traffic to a national news website might be intra-continental and thus not traverse an undersea cable. Instead, such traffic only traverses the customer-facing access network, the metro network in the customer region, the long haul network, the metro network in the data center region and an edge router in the service provider data center.

<sup>1</sup> In our model, we neglect this additional network link in order to simplify the model structure.

<sup>2</sup> As opposed to multicast or broadcast where data from one source node is directed to multiple destination nodes.

### 3. Methodology

#### 3.1 Bottom-Up Model

The energy footprint of an individual service (as opposed to the total energy consumption of the entire network) is a share of the energy consumption of the network devices that carry data between end points. For any given connection between a user and a server, not all devices in the network will carry the connection data. This will be done only by devices in the specific route, which for illustration can be thought of as the shortest connection through the network between the end points which does not contain circles. The energy intensity is a metric in which the per-device energy intensity over all devices in the typical route between end points is summed up. The energy intensity of a device is the ratio between its energy consumption (including overheads for cooling and power transformation) and its actual data throughput. Actual data throughput differs from nominal data capacity as it takes actual utilization or unused capacity into account.

The model distinguishes between metro and backhaul networks and separately undersea connections. The structure of the model is similar between metro and long haul networks. The full model including implementation details for computational simulation is available at [11].

We exclude the access network (see previous chapter and the inter-data center networks). For the metro segment, the energy intensity is estimated per router and then summed up over all routers involved. Optical transport networks are also included. They too are modeled by the energy intensity per individual device, which is then summed up over all transport devices. The structure for the long haul network is assumed to be identical to the metro network, while the energy intensity per router is lower but the number of optic transport devices is higher. The device energy intensity is multiplied by a PUE value, and overheads for utilization and redundancy are applied. For illustration, the energy intensity of the metro transmission network is estimated as:

$$I_{MIM} = R \cdot n_{MR} (c_{ON} \cdot I_{ON} + n_{MOA} I_{OA})$$

where  $R$  is redundancy,  $n_{MR}$  the number of metro routers,  $c_{ON}$  the ratio of WDM systems relative to routers,  $I_{ON}$  energy intensity per WDM system,  $I_{OA}$  the energy intensity per optical amplifier and  $n_{MOA}$  the number of metro network optical amplifiers per hop.

#### 3.2 Parameterization

Accuracy of model-based assessments depends on the amount of uncertainty contained in the model assumptions. A structured approach to identifying such sources of uncertainty distinguishes between aleatory and epistemic uncertainty. Aleatory uncertainty refers to non-reducible statistical variance in the processes modeled, which is

typically described with random variables that in turn can optionally be represented by average values. While such uncertainty prevents precise prediction, it does not affect the accuracy of model results inside the combined bounds of the underlying uncertainty variables.

An example of aleatory uncertainty is deciding on capacity for servers in response to anticipated demand, which depends on the time users access the service: For some services, such as reading news on a tablet, it might not be possible to predict when a particular customer will access the service. Nonetheless, the service provider can collect time series data on the basis of which he can make a statistical inference the accuracy of which only depends on the accuracy of the underlying random variable. Although the service provider might not be able to predict a visit by a specific user, his model might be accurate enough to predict demand most of the time.

If the model fails to predict occasional spikes of demand, for example as a response to political events, this would be a form of epistemic uncertainty, as knowledge about the system was inaccurate. Models for which the predictions can be tested against some empirically measured data become corroborated, and confidence in their accuracy increases. In the example above, corroboration occurs when actual demand is within the predicted bounds.

If empirical data to corroborate models is lacking, then epistemic uncertainty can result in significant discrepancies between predicted and actual system performance.

Therefore, it is necessary to improve understanding of the system by including expert opinion and corroboration of model parts where possible. These efforts can be directed by performing sensitivity analyses: identifying those model parts that contribute most strongly to the model result and are thus most relevant. Computation models can evaluate the overall variance through Monte Carlo-style sampling simulations. It is however important to note that sensitivity analysis does not express epistemic uncertainty – it makes no statements about how closely a model parameter is to the actual system property but only how strongly certain assumptions affect the prediction result.

Once a sensitivity analysis has identified the most relevant variables, experts can be consulted for the calibration of the model. For example, ISPs could report the model and configuration of all network equipment to a central database where each model was listed with energy consumption on which to base calculations. Similarly, the capacity and utilization of devices could be learned.

In the model presented here, the parameters are selected from recent peer-reviewed academic works as well as manufacturer specification, notably [12-15].

**Edge Switch Energy Intensity.** Devices in the edge network include switches that connect devices but also routers that provide services to the access network and are more energy intensive. For the switch we assume an energy intensity of 8 Joule per Gigabit (J/Gb) and for the router we apply a triangular distribution with a min of 16J/Gb, mode of 40J/Gb and max of 137J/Gb, resulting in an average of 64 J/Gb.

**Router Energy Intensity.** The mean energy intensity of the entire population of metro routers in our model is 39 J/Gb. OTN router interface modules are accounted for as part of the router energy efficiency such that when added together they result in an intensity of 16.1 J/Gb for metro routers. For long haul routers the average value energy intensity is assumed to be between 17.2 J/Gb and 50 J/Gb for the most and least efficient configurations with either all or only one line card slot filled, with an average intensity of 26.7 J/Gb. Given the relatively close range of the sample points with only two outliers, we parameterize our model by resampling from a Gaussian kernel density estimated distribution over all values for both long haul and metro routers.

**Route Length and Router Count.** For the average route length representing connections from both residential setups as well as campus networks, we assume that the value of 6 routers plus aggregation switch on the edge to the access network is representative. In our simulation we evaluate the sensitivity of the energy intensity by applying a triangular distribution with a min value of 3, a mode of 6 and a maximum of 8 routers. *Long haul Networks.* For connection within the same continent or country, a value of 4 is likely to be representative. For transcontinental connections, the count of long haul routers is likely to be higher. In our model we apply a triangular distribution with a minimum of 4, mode value of 6 and maximum of 8 routers with a mean of 6.

**WDM Terminals and Amplifiers in Edge and Core.** We assume all interoffice transmission is via WDM systems. We assume a cumulative, nominal energy intensity of the optical transmission system to vary between 230, 147 and 316 J/Gb (average, 25th, 75th percentile) for metro and 1593, 893 and 2292 J/Gb (average, 25th, 75th percentile) for core networks, respectively. On top of this nominal energy intensity, overcapacity will be allocated for as described below.

**Network Utilization.** Results from the bottom-up model are strongly influenced by assumptions of the network utilization or overcapacity. This refers to the difference between maximum capacity, which serves as the basis for the calculation of the devices' energy intensity, and the actual use of capacity. We assume that long haul networks are utilized to around 33% on average (utilization factor of 3). We assume the same value for fiber optic links. For the sensitivity analysis we apply a triangular distribution with a min of 2 (50%), mode of 3 (33%) and max of 5 (20%), which results in a mean of 3.33 (30%).

For the metro networks, we assume that utilization values are lower and use a triangular distribution with a min of 4 (25%), mode of 6 (16.67%) and max of 10 (10%), resulting in an average value of 6.67 (15%).

**PUE and Redundancy.** We follow the existing studies that all assume a PUE of 2.0. We further assume that commercial ISPs operate redundant nodes and apply a factor of 2.0.



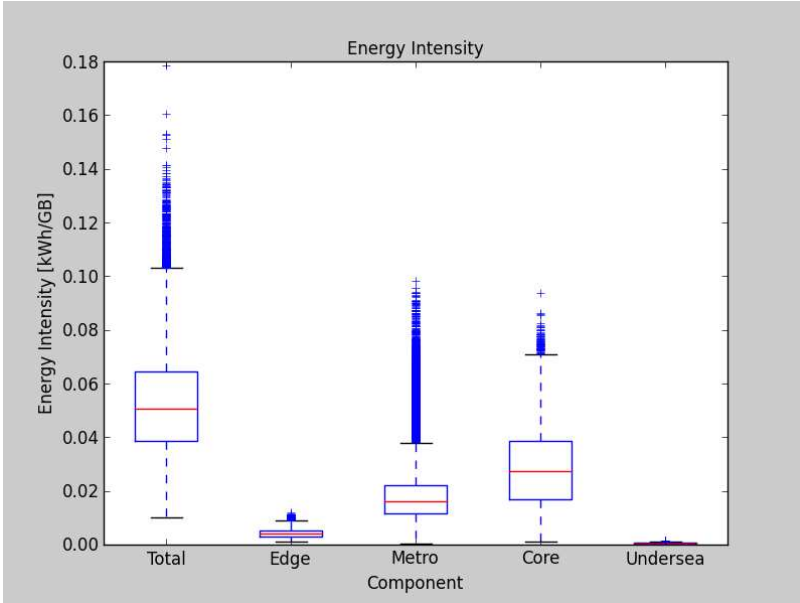
**Undersea Traffic.** We model undersea traffic by intensity per distance and vary the intensity parameter uniformly between 0.026 J/Gb\*km and 0.123J/Gb\*km with an average of 0.0745 J/Gb\*km. We vary the distance uniformly between 6000 km and 12000 km. The portion of traffic that crosses an undersea cable varies depending on the location of the user. For users from the US, on average fewer content and services will be delivered via undersea cable than for users in other parts of the world. In order to evaluate the influence of this value, we vary it over a uniform distribution with min of 10%, a maximum 50% and a resulting average of 30%.

## 4. Results

### 4.1 Absolute Results

Given the above variable values and model structure, the average energy intensity of data traffic through edge, metro and long haul networks including an undersea cable link, but excluding access networks, evaluated to Kilowatt-hours per Gigabyte (kWh/GB) 0.052 kWh/GB. The contributions by the route segments in edge, metro and long haul network are 0.0043, 0.02 and 0.028 kWh/GB, respectively.

Figure 3 shows a whisker plot of the distribution of network energy intensity as result of the Monte Carlo simulation. The 1<sup>st</sup> and 3<sup>rd</sup> quartiles are positioned at 0.039 kWh/GB and 0.064 kWh/GB, respectively.



**Fig. 3.** Whisker plot of the distribution of total energy intensity and its components from the Monte Carlo simulation of the results. The red line represents the median values. The top and bottom borders of the boxes represent the 1st and 3rd quartiles, respectively. Outliers are those points that are more than 1.5 standard deviations from average and are marked with crosses.

## 4.2 Sensitivity Analysis

In order to understand how strongly the uncertainty of each parameter affected the overall result, a sensitivity analysis based on Monte Carlo style resampling was applied. Based on the resulting distribution, Spearman ranks for the model parameters were calculated. These rank values are correlation scores that represent the direction in which the total result changes with a change of a model variable on an interval between -1 and 1. A score of 0 means that there is no correlation at all, 1 means perfect correlation and -1 means perfect anti-correlation.

Table 2 shows the Spearman ranks of the most relevant model variables (rho greater than 0.1). The table contains subcomponents (*italics*) as well as subcomponent variables.

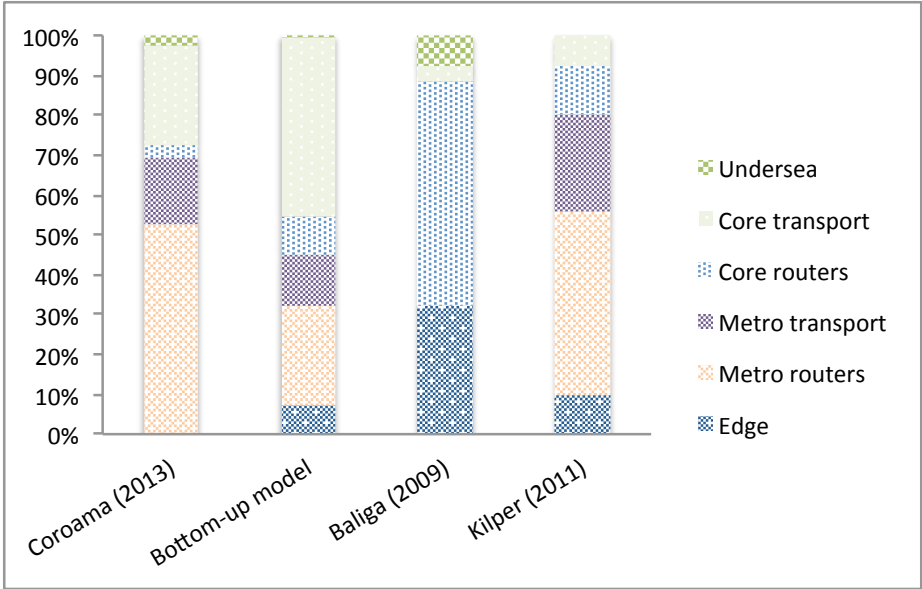
**Table 1.** Spearman ranks of model components with a rank greater than 0.1. *Italic titles* denote entire network layers. Normal font denotes variables representing device characteristics.

<i>Component</i>	<i>Spearman rank</i>
<i>Long haul</i>	0.77
<i>Long haul Optic Component</i>	0.73
<i>Long haul Transmission</i>	0.67
<i>Metro</i>	0.54
<i>Metro IP component</i>	0.50
Metro Router Energy Intensity	0.44
<i>Long haul IP component</i>	0.27
Long haul Overcapacity	0.26
<i>Metro Optic Component</i>	0.22
Long haul Router Efficiency	0.21
Metro Overcapacity	0.18
<i>Metro Transmission</i>	0.16
Number Metro Routers	0.11

According to this, long haul networks are more significant than metro networks. For both long haul and metro networks, the optic transmission layer (transmission system and fiber terminals) is more energy intensive than the routing layer.

Figure 4 shows the model results in comparison with the three models that are the most relevant sources for parameters and model structure. In order to make these studies comparable, we set the system boundaries to include a path that each study covers: only one leg of the edge, metro and long haul networks. In this way, we can calculate network paths. Depending on the number of segments included, the model will be more or less representative for regional specificities.

The results of the current model are displayed in column 2. The study [12] finds that long haul transmission networks are far more relevant to the overall energy intensity than long haul routers. The studies by [14] and [13] on the other hand reach the opposite conclusion. The parameterization of the current model is a combination of both perspectives. The disagreement indicates the need for more investigation.



**Fig. 4.** Relative composition of energy intensity of Internet data traffic in this model (2nd column) and relevant previous studies.

5. Discussion

An energy footprint of a digital service is a share of the energy consumption of the network. The energy intensity provides a metric that yields this share when multiplied by the data volume per service. The energy intensity metric presented here can be used to calculate a balanced account of energy consumption: if the assumed values for the energy intensity are correct, then the sum of the energy footprints of all services equals the total network energy consumption if no double counting of data volumes occurs.

The energy intensity depends on the network layers taken into account. For the majority of cases this will include all layers presented in section 2: the metro network twice, the long haul network and optionally a leg of undersea transport. The undersea transport might be excluded for a share of traffic that is known to be intra-continental.

A necessary step in the calculation of the footprint is thus the collection of all data traffic that is part of a service in an inventory. Separate inventories of data volumes might be appropriate for traffic in separate network segmentations. Care must be taken that all data sources are accounted for. Specifically, many online services draw data not just from the servers of the service provider but also include data from third parties.

The energy footprint is then calculated from the product of energy intensity and the data volume. For a full assessment, the energy intensity of access networks (see previous chapter), campus network and in-data center network devices (including firewalls and load balancers) must be added to this.

In our model we estimate the total energy intensity of the typical route through the Internet between two endpoints, typically user and server, mainly based on the energy intensity per router and optical terminal, by dividing their power consumption by the average data throughput of the device. This step is a form of allocation that is supposed to provide an apportioning of a flow **with a significant environmental impact** (here energy consumption) between multiple outputs (here all Internet connections world-wide) when necessary. Because energy consumption in network devices is highly inelastic [16], [17], the energy intensity should not be used for change-oriented assessments of energy footprints.

For the estimation of carbon footprints from energy footprints, we suggest using per-continent average carbon intensity values for electricity because of the high uncertainty around the location of core network devices.

The update of these results is strongly encouraged. If new expert knowledge becomes available, for example for a specific region, the parameter values should be adjusted. The modular structure of the model should accommodate this. For example, the submarine cable component is completely additive and can be excluded if it is known that a service reaches an intra-continental audience exclusively.

## 6. Example Footprint Calculation

As an illustration of the use of the energy intensity metrics described in this and the previous chapter, we compare the network energy consumption from watching 1 hour of video stream in HD quality from the BBC iplayer service to browsing an online news service such as The Guardian website for 1 hour and reading articles. We assume that the user is based in the UK and that content is consumed with an iPad connected via WiFi to a DSL Modem with integrated WiFi router, which is in turn connected to a DSLAM and then the rest of the Internet. In our example, we exclude the energy consumption of the server.

Given the model of the access network presented in the previous chapter [18] and this one, we estimate the energy consumption by time for the access network and by data volume for the metro and long haul networks. Given the parameters provided for customer premise network equipment and the DSL access multiplexer, and allowing for overheads for idle standby of customer equipment, we estimate that the effective power consumption per subscriber household is about 52 W. Thus, the total energy consumption of a service can be described as:

$$E(S) = t(S) * 52W + GB(S) * 0.052 \text{ kWh/GB}$$

where  $t(S)$  is the time of the service, 52 W the estimate for the average consumption of access networks and CPE,  $GB(S)$  the amount of data sent and received by the service (measured in GB), and 0.052 kWh/GB the estimate for the average energy intensity of long haul and metro networks.

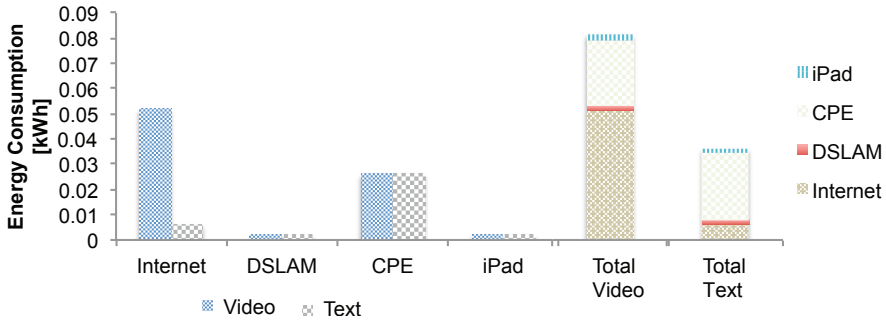
In order to emphasize the varying intensity of the network parts, we assume that the duration of both activities is identical. During that one hour, the user is assumed to

continuously visit different articles at an average rate of one article per minute or continuously receive the video stream. The news web pages are assumed to have an average size of about 2 MB per page. **Table 2** contains the input data for our calculation. We assume the video stream results in a total data volume of 1 GB being downloaded during the one hour duration. We further assume that the iPad consumes 2.4 W while showing video and browsing the web.

**Table 2.** Input data and results for video and web browsing scenarios. Time is given in seconds s, Page size in Megabyte MB, Data Volume in Gigabyte GB, Video bit rate in Kilobyte per second KB/s, Internet energy intensity in Kilowatt-hours per Gigabyte kWh/GB. Power consumption values are stated in Watt W. Energy consumption in Joule J and Kilowatt-hour kWh.

	<i>Video</i>	<i>Text</i>	
Time per page	-	60	s
Pages	-	60	-
Page size	-	2	MB
Bit rate	278	-	KB/s
Data volume	1	0.12	GB
Time	3600	3600	s
Energy intensity	0.052	0.052	kWh/GB
Power DSLAM	2	2	W
PUE	2	2	-
Power CPE	8	8	W
Idle overhead	6	6	-
Power iPad	2.4	2.4	W
<b>Energy Consumption</b>			
Internet	0.052	0.00624	kWh
DSLAM	0.004	0.004	kWh
CPE	0.048	0.048	kWh
iPad	0.0024	0.0024	kWh
Total	0.1064	0.06064	kWh

We assume the power consumption is constant during that time and estimate that the total energy consumption is 0.11 kWh for one hour of video watching and 0.06 kWh for one hour of browsing news.



**Fig. 5.** Comparison of total energy consumption and system components when streaming 1 hour of HD video or browsing a news website for 1 hour.

Figure 5 illustrates the results. While the energy consumption by the access network equipment and the user device does not vary, as these are independent of the data volume transferred, the estimated energy consumption by the network varies substantially. For relatively low data volumes, most energy is consumed by the customer premises equipment. As the data volume transferred by the service grows, the long haul and metro routers become the dominating factors.

## 7. Conclusion

In order to estimate use-phase energy footprints and carbon footprints of digital services, estimates of energy intensity of the Internet can be of use. In this text we have combined the current empirical evidence and insight into the structure of the Internet to estimate the energy intensity of the Internet for environmental assessments of digital services. The energy intensity metric we propose is based on a model segmented into metro, long haul and undersea traffic and, combined with digital service data volume, yields estimates of a service energy footprint.

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